

CORONAL HEATING AND EMISSION MECHANISMS IN AGN

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ABSTRACT

Popular models for the formation of X-ray spectra in AGN assume that a large fraction of the disk's angular momentum dissipation takes place in a hot corona that carries a small amount of the accreting mass. Here I discuss the formation of a magnetically-structured accretion disk corona, generated by buoyancy instability in the disk and the heating of localized flare regions up to the canonical X-ray emitting temperatures. I also examine the analogy between accreting disk-coronae and ADAFs and discuss the relevant emission mechanism in these two accretion models and how observational constraints can allow us to discriminate between them.

KEYWORDS: accretion, accretion disks; magnetic fields; radiation mechanisms: thermal; X-rays: general

1. INTRODUCTION

Observations of the central regions of AGN show that a significant fraction of their bolometric luminosity comes out in hard X-rays (from ~ 0.1 keV all the way up to a few 100 keV) and sometimes up to 1 GeV.

According to the standard paradigm, AGN are powered by accretion onto their central black hole. An accretion disk around a supermassive black hole (in an AGN) leads to the production of a strong optical/ultraviolet continuum, the so-called 'blue bump'. Such a component is attributed to quasi-blackbody emission (e.g. see Koratkar & Blaes 1999 for relevant modifications to the blackbody spectrum for an accretion disk). The effective absorptive optical depth in a disk is typically $\tau >> 1$ which implies that photons are close enough to being in thermal equilibrium with the electrons to produce a blackbody-like spectrum. The luminosity of this component scales as $L \sim \pi r_g \sigma T^4$ where r_g is the Schwarzschild radius. This implies gas temperatures in the disk of the order of

$$T \sim 5 \times 10^5 L_{44}^{-1/4} \left(\frac{L}{L_{Edd}} \right)^{1/2} K, \quad (1)$$

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where $L = 10^{44}L_{44}$. L_{Edd} is the Eddington luminosity and the temperature decreases with increasing luminosity (or increasing black hole mass).

It is evident from Eqn. 1 that if AGN generated their energy solely by accretion of matter in thermodynamic equilibrium, the highest temperatures achieved would be of the order of 10^5 K and negligible X-ray emission would be expected. Phenomenologically, therefore, we know that there must be an efficient mechanism for transferring the energy released in an accretion disk into a plasma component that is far from thermodynamic equilibrium with the ambient radiation and that radiates the high energy portion of AGN spectrum.

Although there are many uncertainties concerning how such energy transfer occurs, we know there must be mechanisms that can sustain the presence of a very hot plasma near an accretion disk: e.g. the Sun which has a the surface temperature of only 5500 K, is surrounded by a magnetically-dominated corona with a temperature of $2 - 3 \times 10^6$ K.

Here, I address the issue of why we expect hot electrons to be present in AGN. I will discuss how AGN coronae formation can be understood as a direct consequence of the internal dynamics of an accretion disk where shock-like events (magnetic reconnection and MHD processes) are responsible for heating the coronal plasma. I will examine the relevant radiative processes in AGN that are responsible for the production of the X-ray emission that we observe. In particular I will discuss the relevance of these processes for both AGN coronae and hot advection-dominated accretion flows (ADAFs) and their relative importance for different regimes of source luminosities.

1.1. The X-ray emission

Before discussing in more detail the proposed picture of coronae formation I will briefly review the observed characteristics of the X-ray emission in AGN and the information that these give when trying to construct a model for coronae.

Assuming for now the existence of a hot plasma (see Section 2), it is well established that the X-ray continuum in AGN can be explained by thermal Comptonization of the soft UV radiation (e.g Haardt & Maraschi 1993). There is evidence also that this X-ray continuum is reprocessed in a cold medium (e.g. the accretion disk) and gives rise to a reflection bump at around 30 keV and a broad iron, Fe $K\alpha$ emission line at 6.4 keV. The presence of these features in the spectrum place constraints on the geometry of the X-ray emitting region and tell us that the hot plasma has to be situated above the colder accretion disk. Also, the different ratios of soft luminosity (attributed to the accretion disk) to hard X-ray luminosity imply that the hot coronal plasma is not a slab but consists of localized active regions (e.g. Haardt, Ghisellini & Maraschi 1994). This is also consistent with the characteristically short X-ray variability timescales observed in Seyfert galaxies (as short as a few hours) which imply that enormous amounts of energy are released in a very short time in flare-like events.

Finally, the average X-ray spectra of Seyfert galaxies shows a high-energy cutoff

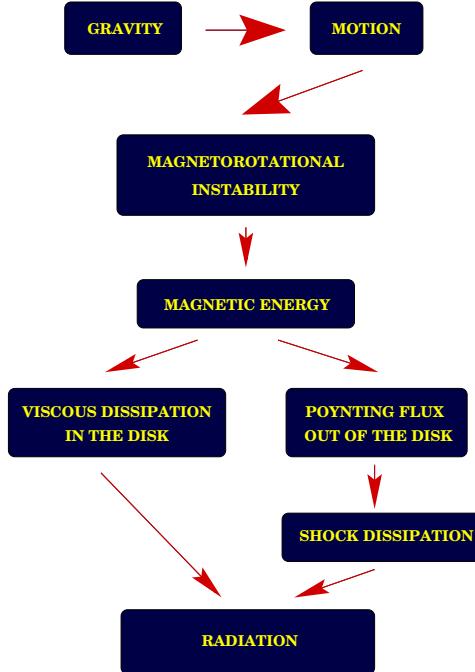


FIGURE 1. Energy flow and angular momentum transport in accretion disks

usually above 100 keV which can be reproduced quite well by models of thermal Comptonization. The absence of conspicuous electron pair annihilation line indicates that most of the hot electrons in a corona are thermal. Whatever the processes that operate in coronae to heat the plasmas are, they do not accelerate a large number of electrons. Alternatively, mechanisms exists for efficiently thermalizing the electron population (e.g. Svensson & Ghisellini 1998).

2. ACCRETION DISK CORONAE

In recent years significant progress has been made in understanding accretion disks and how angular momentum transport operates with the identification of the Balbus–Hawley instability (e.g. Balbus & Hawley 1997) for weakly magnetized disks. Thanks to this fundamental progress, we can now think more confidently of coronae formation as a direct consequence of the internal dynamics of an accretion disk; much the same way the solar corona is thought to be heated by dynamical processes lower in the Sun’s atmosphere. More specifically, Balbus & Hawley have identified an instability in weakly magnetized accretion flows that is responsible for the transport of angular momentum. The way such a magneto-rotational instability works is by producing strong amplification of the seed magnetic fields and in this way channelling the energy present in the system into magnetic energy (see Figure 1). The formation of a corona can be understood as an efficient way for a disk to saturate the Balbus–

Hawley instability and to dissipate the accretion energy/angular momentum into particles, which can then radiate it away. The built-up magnetic energy is dissipated into particles locally in the disk and partly builds-up strong magnetic flux tubes leading to a net vertical flux of magnetic energy which inevitably escapes from the disk to form a magnetically-dominated corona.

The idea that buoyancy of strong flux tubes in the disk and their expulsion from the disk to form magnetic coronae has been proposed in the past (Stella & Rosner 1984, Coroniti 1981, Galeev, Rosner & Vaiana 1979), but can only now be integrated in a deeper understanding of accretion phenomena.

2.1. Coronal heating: magnetic reconnection

Within the context of such a model, the question of how the coronal plasma heats up to X-ray emitting temperatures can be assessed. Such coronae (e.g. ensembles of flux tubes) contain a very small amount of mass and are magnetically dominated. By definition, the magnetic flux tubes become buoyant when $\beta \sim 8\pi P/B^2 \gtrsim 1$ where B is the magnetic field strength and P the gas pressure in the disk. The typical speed of the rising flux tubes is then given by their Alven speed e.g. $V_A = B/\sqrt{4\pi\rho} \gtrsim c_s$ and is by definition always larger than the relevant sound speed (c_s) implying (in a simple view) that the buoyant magnetic energy has to be dissipated in shocks. So, whereas the core of the disk is usually dominated by subsonic turbulence the coronal gas above the disk is, inevitably, supersonic.

More realistically we would expect this energy to be dissipated in shocks in reconnection sites where strong impulsive heating occurs when magnetic field lines are brought together. Reconnection can occur either ‘spontaneously’ in a given magnetic loop or can be ‘driven’ when more than one magnetic tubes are brought together. A reconnection site is thought to be a collection of particle acceleration and heating (e.g. direct Joule heating near X-point, slow shock acceleration, Fermi magnetic mirroring in turbulent outflows, conduction, downstream fast shocks etc..) but the detailed physics of how it occurs is still an unsolved MHD problem (for the case Petschek reconnection).

Although the general physical picture of accretion disk coronae described above provide us with an understanding of why we expect to find hot plasmas above accretion disks, there remain many uncertainties. These include the question of which pressure is relevant for magnetic field amplification and buoyancy. It is not clear whether magnetic fields build up to equipartition such as $B^2/8\pi \sim P_{tot}$ or $B^2/8\pi \sim P_{gas}$. Also, it is uncertain what fraction of the magnetic energy is dissipated into e^- and p . It is clear that when energy dissipation occurs one needs to treat the plasma as a 2-temperature medium: different wave-particle interactions will heat electrons and protons differently. One can construct 2-T AGN coronae if the protons contain most of the energy (Di Matteo, Blackman & Fabian 1997), but no clear-cut arguments can be made to support their plausibility over one temperature models. The same problems exist in the case of ADAF plasma where the 2-T condition is a crucial assumption but, at this stage, yet to be proven. Coronal plasmas are often

collisionless. It is not clear, therefore, whether electrons are thermalized or dissipative processes cannot accelerate particles efficiently. In other words the importance of direct heating versus acceleration in either coronal or ADAFs plasma, cannot be determined. In AGN coronae or ADAFs, V_A can approach c , and one should really consider the effects of relativistic MHD. Such effects are usually not taken into account.

Important recent results from numerical simulations (Miller & Stone 1999) do indeed show the formation and heating of magnetized coronae above accretion disks. In particular, Miller & Stone have shown that when weak B fields are amplified in the disk via MHD turbulence driven by the Balbus–Hawley instability some of the magnetic energy is dissipated locally but a good fraction escapes due to buoyancy and forms a strongly magnetized corona above the disk. Most of the energy in their simulations is dissipated at a few scale heights above the disk, and strong shocks are continuously produced making the corona hot up to X-ray emitting temperatures. Their results on the impulsive heating of coronal plasmas, are in accordance with simple analytical estimates (Di Matteo 1998) on the occurrence of an ion–acoustic instability, associated with slow shocks in Petschek magnetic reconnection in flare-like events in a magnetically-dominated corona. The occurrence of an ion–acoustic instability, associated with slow shocks in Petschek magnetic reconnection, can be shown to result in a violent release of energy and heat the coronal plasma to canonical X-ray emitting temperatures (of a few $\times 10^9$ K).

3. EMISSION MECHANISMS

In the previous sections I have discussed the vertical structure of an accretion disk and how its internal dynamics can lead to the formation of a highly-dynamic, magnetically dominated and heated corona.

Both in AGN coronae and in ADAFs (also magnetized and with hot $\sim 10^9$ K electrons; see Narayan, Quataert & Mahadevan 1999 for a recent review) the relevant interactions and relative emission mechanisms are: particle-photon \rightarrow Compton processes; particle-magnetic field \rightarrow cyclo/synchrotron emission and particle-particle \rightarrow bremsstrahlung emission.

Inverse-Compton scattering of disk photons off the hot electrons is usually the dominant process in most AGN. The importance of Inverse-Compton processes scales $\propto U_{rad} \exp(y)$ where $y \sim 4(kT/m_e c^2)\tau$, $\tau = n_e \sigma_T r$ and the energy density $U_{rad} \sim L/(R^2 c)\tau$ is usually attributed to the external soft photon flux coming from the disk. Bremsstrahlung instead scales as $n_e^2 T^{-1/2}$, where n_e is the electron number density, and dominates IC only in very low luminosity objects e.g.

$$IC > BREM \rightarrow \frac{L}{L_{Edd}} > \frac{10^{-5}}{\sqrt{\theta}} r_s \quad (2)$$

(see also Section 3.2), where θ is the dimensionless electron temperature.

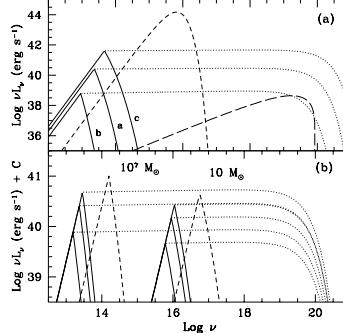


FIGURE 2. (a) The solid line is the synchrotron component, the dotted line its Comptonization, small dashed line the blackbody component form the accretion flow. (b) The shift in frequency of the synchrotron peak between supermassive and galactic black holes.

3.1. Synchrotron emission and Comptonization in coronae and ADAFs

Both in the case of an AGN corona or an ADAF, magnetic fields are close to their equipartition values and synchrotron emission should be taken into account.

In both cases electrons are considered to be thermal. Thermal synchrotron is heavily self-absorbed up to a frequency $\nu_s \propto T^2 B$. Equipartition arguments (in the case of a supermassive black hole with $M \sim 10^7 M_\odot$) imply values of $B \sim P_{\text{gas}} + P_{\text{rad}} \sim 10^{3-5}$ Gauss and for canonical corona temperatures of 10^9 K, synchrotron emission peaks in the Infrared/Optical bands (Di Matteo, Celotti & Fabian 1997; see Figure 2a).

The synchrotron soft photon flux is Inverse Compton scattered up to X-ray energies by the hot electrons (dotted line in Figure 2a). In most cases though, synchrotron Inverse Compton does not dominate the X-ray emission because the energy density due to the soft disk photon field dominates the scattering. Due to the high self-absorption, the synchrotron energy density $U_{\text{syn}} < B^2/8\pi$ which, given the equipartition arguments, implies $U_{\text{syn}} < U_{\text{disk}} \sim P_{\text{rad}}$ (Fig. 4a) and Comptonization of the soft disk photons dominates the X-ray emission. Given the strong dependences of thermal synchrotron emission on both temperature and B , and the very dynamical structure of the corona, estimates of an 'average' T and B , which are usually employed in these calculations are likely to be unrealistic. As shown by the above relations, the importance of synchrotron and its Inverse Compton might be highly enhanced if flares are at different temperatures and some are hotter and/or with higher magnetic fields than the values usually assumed from global arguments. It is plausible that a non-thermal population of particles could be present which would also significantly enhance the synchrotron and its IC component but this has not been taken into account in current models).

In contrast, in an ADAF the synchrotron photons are, in most cases, the only source of soft photons for Comptonization (even if the ADAF is matched to a thin

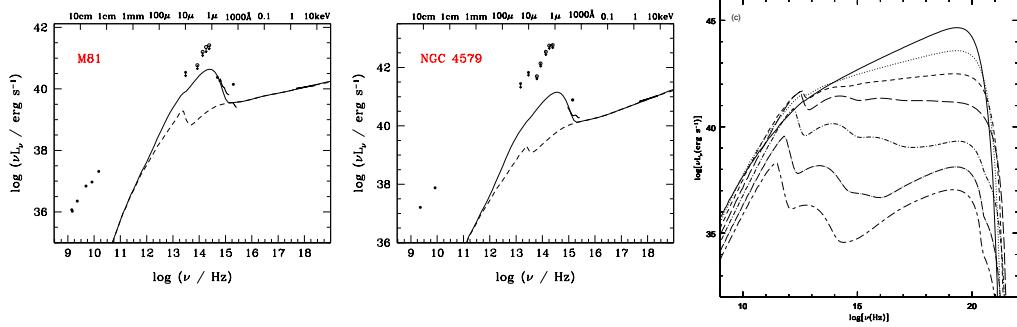


FIGURE 3. Model for M81 NGC 4579 in which a thin disk is truncated at $r \sim 100r_S$, inside of which there is an ADAF. The solid line shows the total "disk + ADAF" emission, while the dashed line shows the ADAF contribution (Quataert et al. 1999). On the rightmost panel the spectra of ADAFs for a $10^9 M_\odot$ black hole with \dot{m} decreasing by about 3 orders of magnitude from the top curve to the bottom one. The high energy spectrum changes from Comptonized synchrotron to bremsstrahlung.

disk at large distances, as in models by Esin et al. 1997; Quataert et al 1999 its contribution is negligible; e.g. see Figure 3).

Comptonization of the synchrotron component in an ADAF can explain the observed X-ray emission in some low-luminosity AGN. Figure 3 shows the case for M81 and NGC 4579 both of which have an estimated mass for the central black hole, detected hard X-ray emission, and optical/UV emission too low to allow for the presence of a geometrically thin, optically thick accretion disk close to the black holes (Quataert et al. 1999). In general, in a standard ADAF, Comptonization becomes important for $\dot{m} \lesssim \dot{m}_{crit}$ above which the hot flow cannot exist. In the high \dot{m} regime considered here, the characteristic electron scattering optical depth τ of the ADAF becomes of order unity since $\tau \propto \dot{m}$. As τ decreases with decreasing \dot{m} , bremsstrahlung becomes the dominant process (see Figure 3).

3.2. Bremsstrahlung emission in elliptical galaxy nuclei

Equation 2 shows that bremsstrahlung emission can only be important in sources with very low luminosities (or low radiative efficiencies). The nuclear regions of elliptical galaxies provide excellent environments in which to study the physics of low-luminosity accretion. There is now strong evidence, from high-resolution optical spectroscopy and photometry, that black holes with masses of $10^8 - 10^{10} M_\odot$ reside at the centers of bulge dominated galaxies, with the black hole mass being roughly proportional to the mass of the stellar component (e.g. Magorrian et al. 1998). X-ray studies of elliptical galaxies also show that they possess extensive hot gaseous

halos, which pervade their gravitational potentials. Given the large black hole masses inferred, some of this gas must inevitably accrete at rates which can be estimated from Bondi's spherical accretion theory. Such accretion should, however, give rise to far more nuclear activity (e.g. quasar-like luminosities) than is observed, if the radiative efficiency is as high as 10 per cent (e.g. Fabian & Canizares 1988), as is generally postulated in standard accretion theory.

Accretion with such high radiative efficiency need not be universal, however. As suggested by several authors (Rees et al. 1982; Fabian & Rees 1995), the final stages of accretion in elliptical galaxies may occur via an advection-dominated accretion flow (ADAF; Narayan & Yi 1995, Abramowicz et al. 1995) at roughly the Bondi rates. Within the context of such an accretion mode, the quiescence of the nuclei in these systems is not surprising; when the accretion rate is low, the radiative efficiency of the accreting (low density) material will also be low. Other factors may also contribute to the low luminosities observed. As discussed by Blandford & Begelman (1999; and emphasized observationally by Di Matteo et al. 1999a), and shown numerically by Stone, Pringle & Begelman (1999), winds may transport energy, angular momentum and mass out of the accretion flows, resulting in only a small fraction of the material supplied at large radii actually accreting onto the central black holes.

If the accretion from the hot interstellar medium in elliptical galaxies (which should have relatively low angular momentum) proceeds directly into the hot, advection-dominated regime, and low-efficiency accretion is coupled with outflows (Di Matteo et al. 1999a), the question arises of whether *any* of the material entering into the accretion flows at large radii actually reaches the central black holes. The present observational data generally provide little or no evidence for detectable optical, UV or X-ray emission associated with the nuclear regions of these galaxies.

The discovery of hard X-ray emission from a sample of six nearby elliptical galaxies (Allen, Di Matteo & Fabian 1999), including the dominant galaxies of the Virgo, Fornax and Centaurus clusters (M87, NGC 1399 and NGC 4696, respectively), and NGC 4472, 4636 and 4649 in the Virgo cluster, has important implications for the study of quiescent supermassive black holes. The ASCA data for all six sources provide clear evidence for hard, power-law emission components, with photon indices in the range $\Gamma = 0.6 - 1.5$ and intrinsic 1–10 keV luminosities of $2 \times 10^{40} - 2 \times 10^{42}$ erg s⁻¹ (Allen et al. 1999). This potentially new class of accreting X-ray source has X-ray spectra significantly harder than Seyfert nuclei and bolometric luminosities relatively dominated by their X-ray emission.

We argue that the X-ray power law emission is most likely to be due to accretion onto the central supermassive black holes, via low-radiative efficiency accretion (Allen et al. 1999, Di Matteo et al. 1999b).

The broad band spectral energy distributions for these galaxies, which accrete from their hot gaseous halos at rates comparable to their Bondi rates, can be explained by low-radiative efficiency accretion flows in which a significant fraction of the mass, angular momentum and energy are removed from the flows by winds. The observed suppression of the synchrotron components in the radio band (Di Matteo

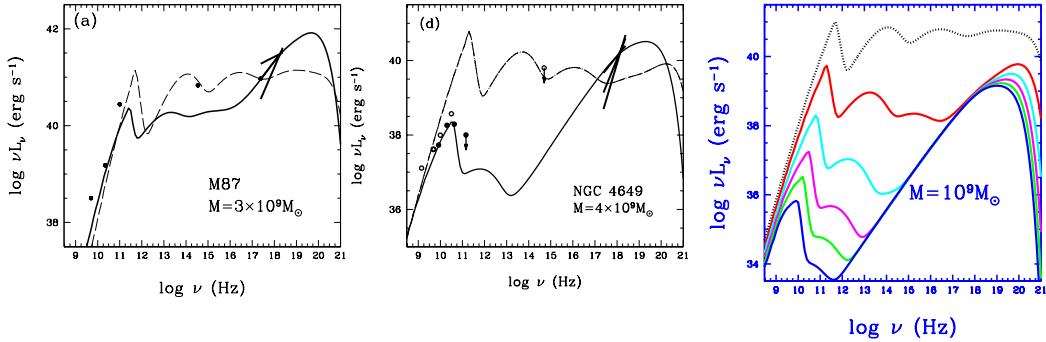


FIGURE 4. Spectral models calculated for ADAF with outflows and without outflows (dashed lines) are shown for two representative cases (for the other objects see Di Matteo et al. 1999b). The solid dots are the best constraints on the core emission. The thick solid lines the slopes and fluxes obtained from the ASCA analysis. The leftmost panel shows explicitly the effects of winds on the spectra of ADAFs, The mass outflow scales as $\dot{M} = \dot{M}_{out} \left(\frac{R}{R_{out}} \right)^p$. Models are calculated for the same \dot{M}_{out} and R_{out} with p increasing from 0 to 1 (in steps of 0.2) from the top dashed curve to the lower one

et al. 1999a; excluding the case of M87) and the systematically hard X-ray spectra, which are interpreted as thermal bremsstrahlung emission, support the conjecture that significant mass outflow is a natural consequence of systems accreting at low-radiative efficiencies (see the representative cases of NGC 4649 and M87 in Figure 4 and for all of the objects Di Matteo et al. 1999b).

The presence of outflows in the hot flows suppresses completely the importance of Comptonization in ADAF flows and bremsstrahlung becomes (irrespectively of the accretion rate, c.f. Figure 3) the dominant X-ray emission mechanism. A representation of the effects on the ADAF spectra of outflows is shown in Figure 4.

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